Cosmic Magnetic Fields From Active Galaxies

Hui Li

Collaborators:

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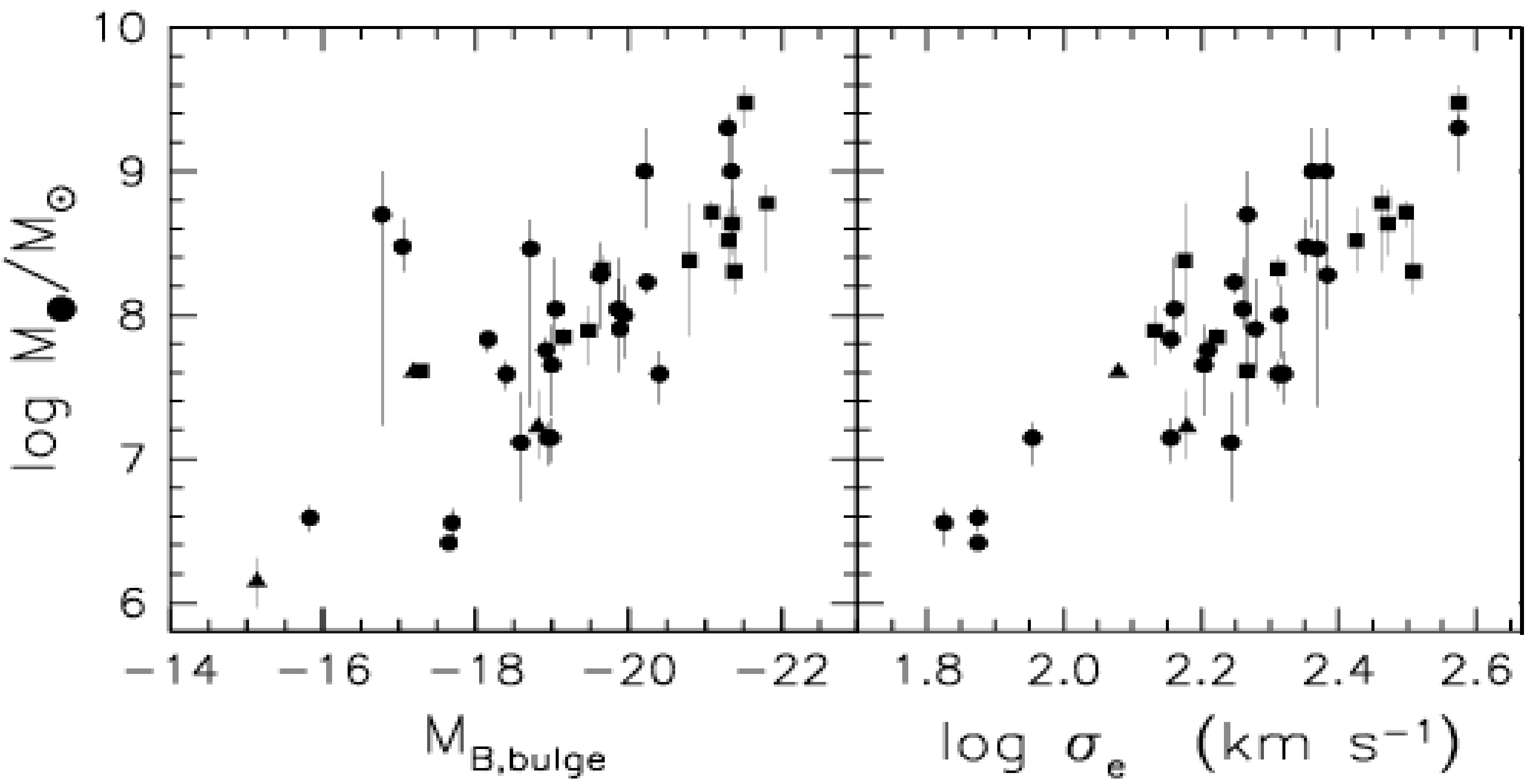
- **Astrophysical observations and motivation:**
  - **Magnetic fields made by active galaxies**
- **Formation of Radio Jets and Lobes:**
  - **a) Helix collimation; b) Radio lobe formation**
- **Implication for Magnetic fields in the IGM**

Ubiquity of Supermassive Black Holes
(Kormendy et al. 2001)

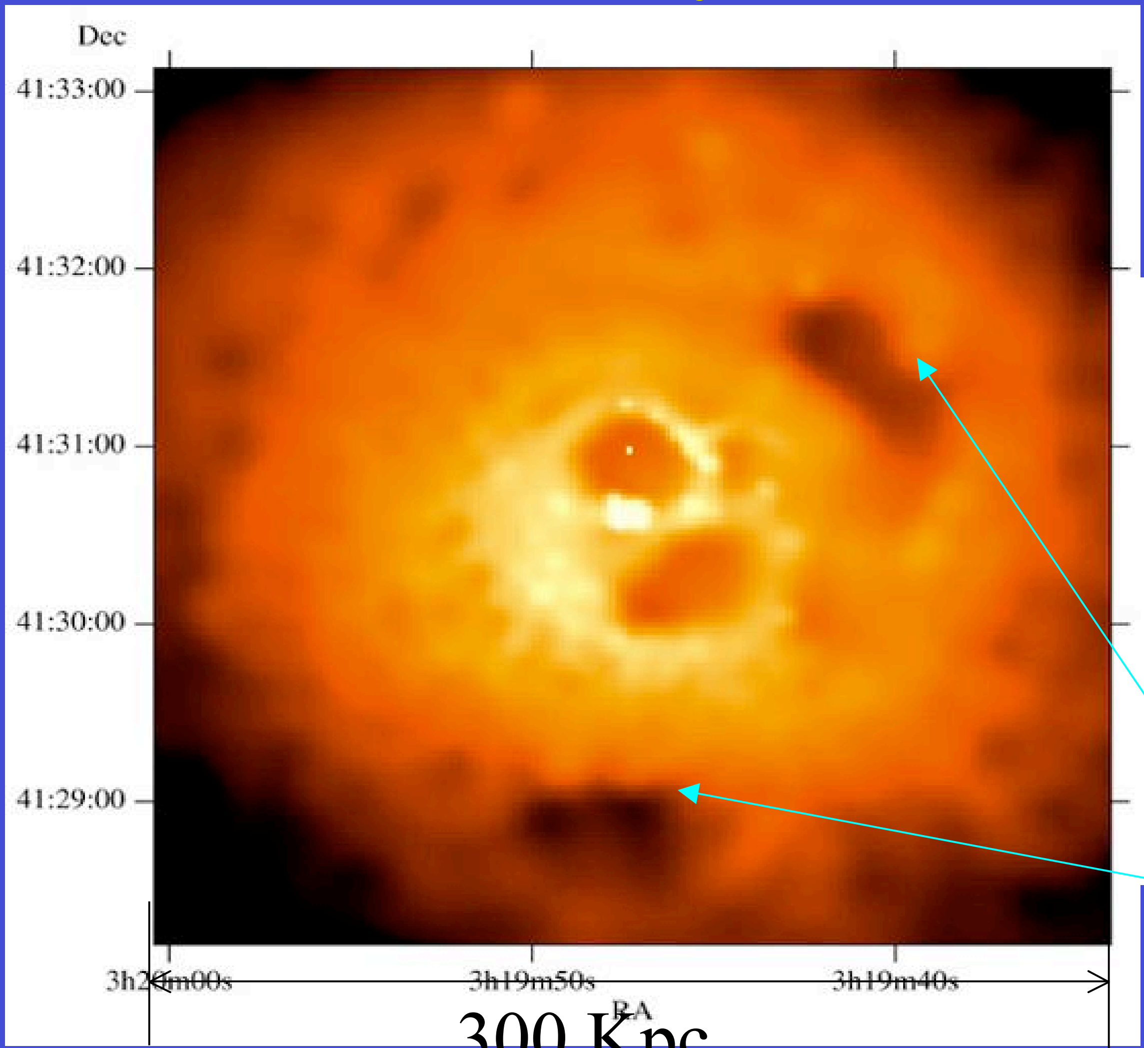


$10^8\ M_{sun}$ → 10^{62} ergs

Where did all the black hole energy go?

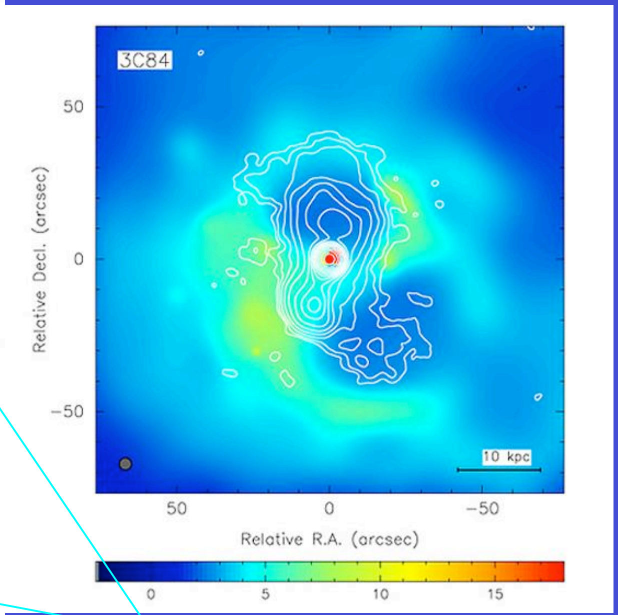
"Cosmic Shoveling"

in X-ray



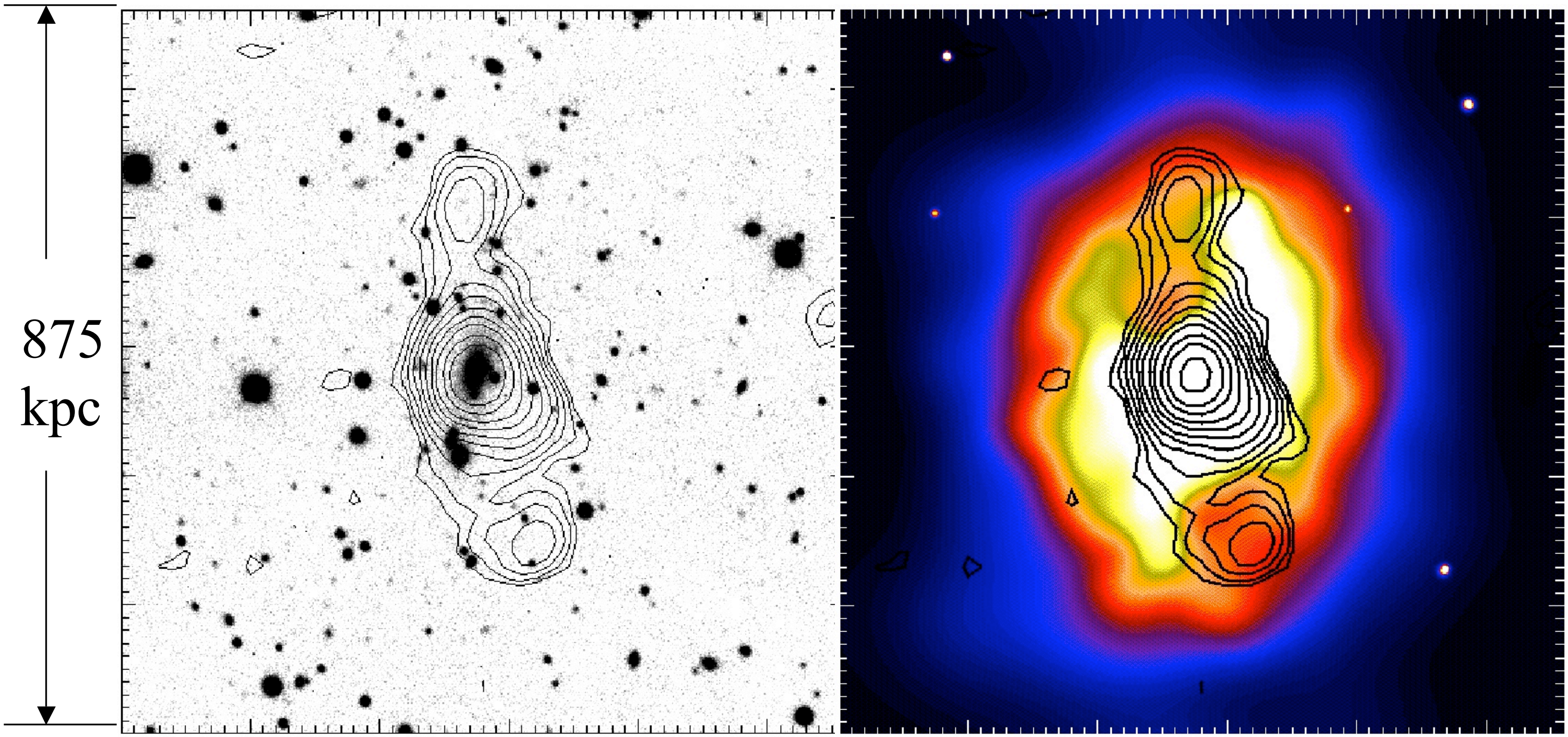
300 Kpc

X-ray + radio



Ghost Cavities
(Previous ejections?)

MS0735



Radio + Optical

Radio + X-ray

Mechanic energy ~ 6 x 10^{61} ergs

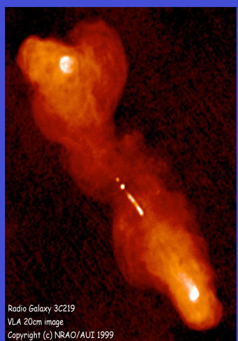
McNamara et al., Nature (2005)

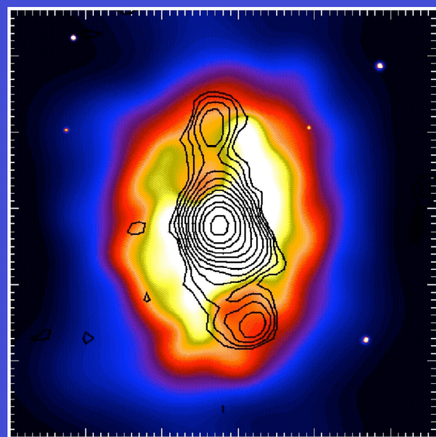
Individual Galaxy

Galaxy Clusters

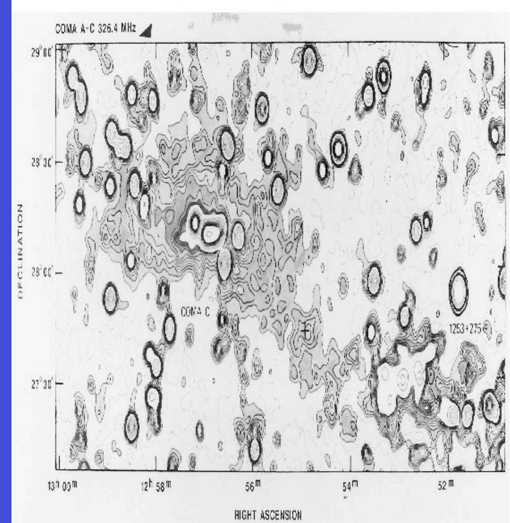
Super-Galactic Filaments

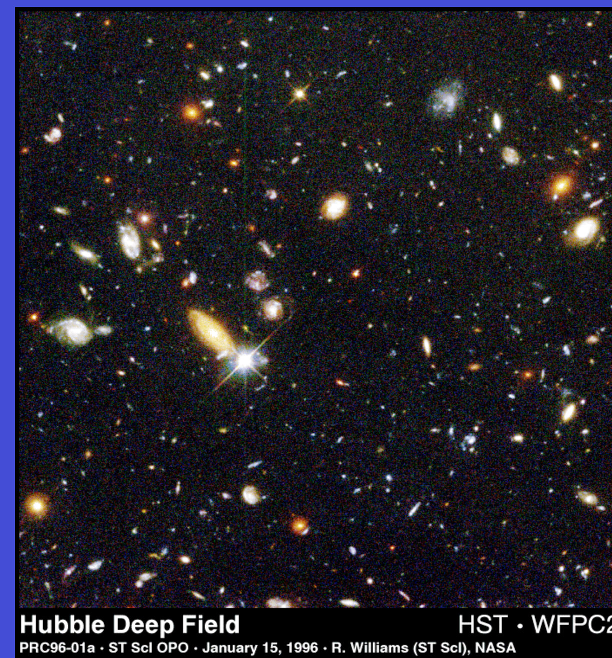
The Magnetized Universe (???)





Adapted from: Kim, Kronberg, Giovannini and Venturi, NATURE, 1989





Questions:

- **Are there wide-spread magnetic fields in IGM?**
  - **Primordial? Dynamo?**
  - **"pollution" by sources: stellar; galactic winds**
  - **"pollution" by Active Galaxies: radio loud AGNs, …**
- **How to observe them?**
- **Dynamically important? Total energy content?**
- **Impact on the physics of IGM?**
- **…..**

Cosmology Ideal-MHD Code

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \bullet (\rho \mathbf{v}) = 0$$

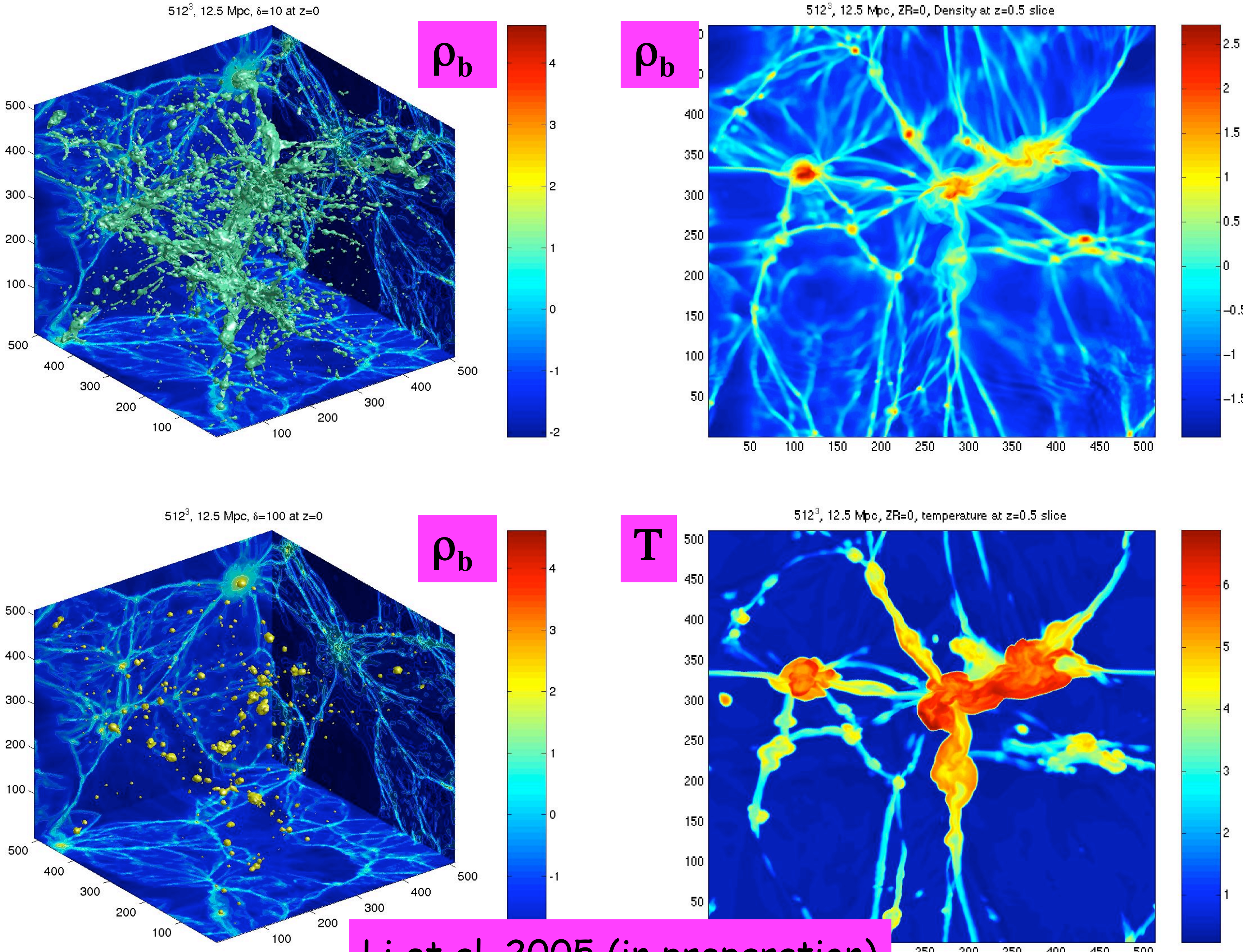
$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \frac{1}{a}\nabla \bullet \left[\rho \mathbf{v}\mathbf{v} + P_g + \frac{B^2}{2} - \mathbf{B}\mathbf{B} \right] = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \Phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \bullet \left[\left(E + P_g + \frac{B^2}{2} \right)\mathbf{v} - (\mathbf{v} \bullet \mathbf{B})\mathbf{B} \right] = -2\frac{\dot{a}}{a}E - \frac{1}{a}\rho \mathbf{v} \bullet \nabla \Phi + \frac{1}{2}\frac{\dot{a}}{a}B^2$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{1}{2}\frac{\dot{a}}{a}\mathbf{B} \ , \qquad E = \frac{1}{2}\rho \mathbf{v}^2 + \frac{P_g}{\gamma - 1} + \frac{B^2}{2}$$

$\rho, P_g, \mathbf{B}$ **: comoving density, pressures;** $\mathbf{v}$ **: proper peculiar velocity**

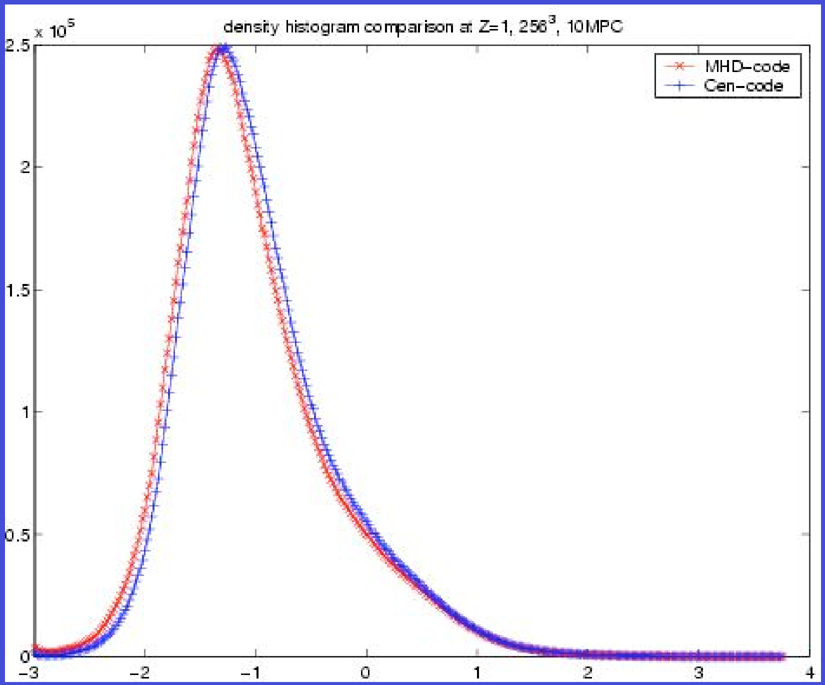
Combine LANL's ideal MHD code (Li & Li'04) with Princeton's cosmology code (Ryu et al.'94, Cen et al.).



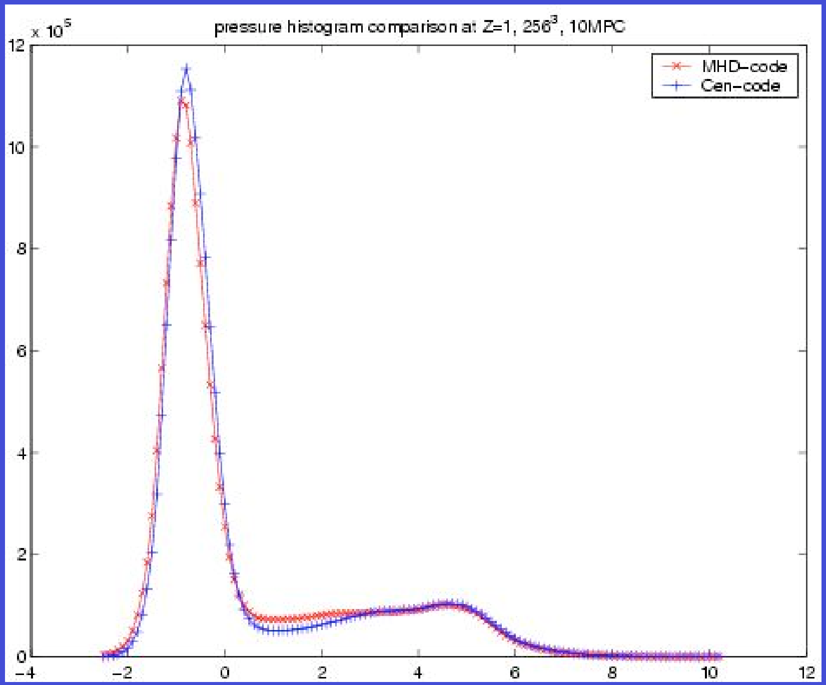
Li et al. 2005 (in preparation)

Code Comparison
(similar to Kang et al.'94)

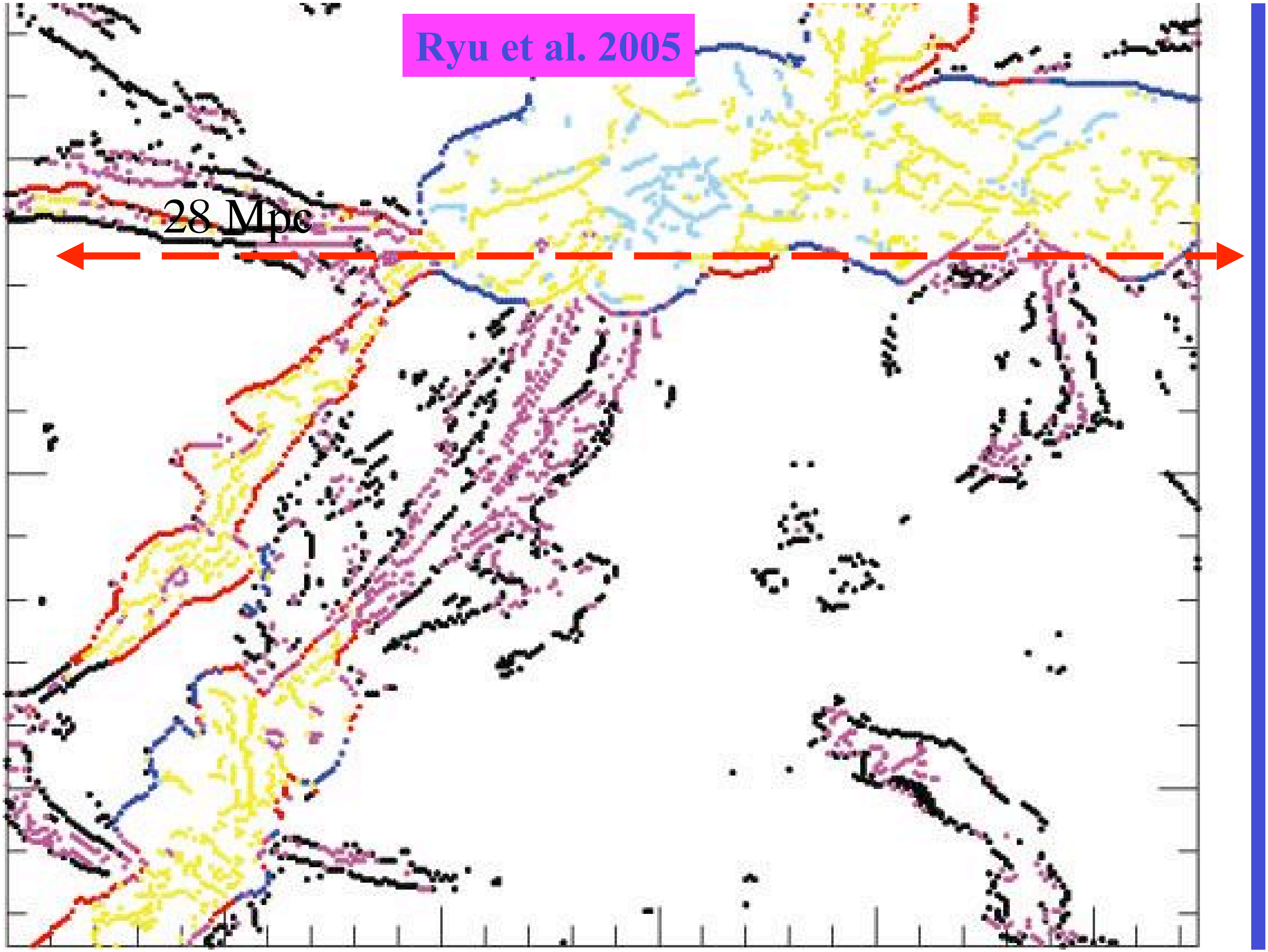
density



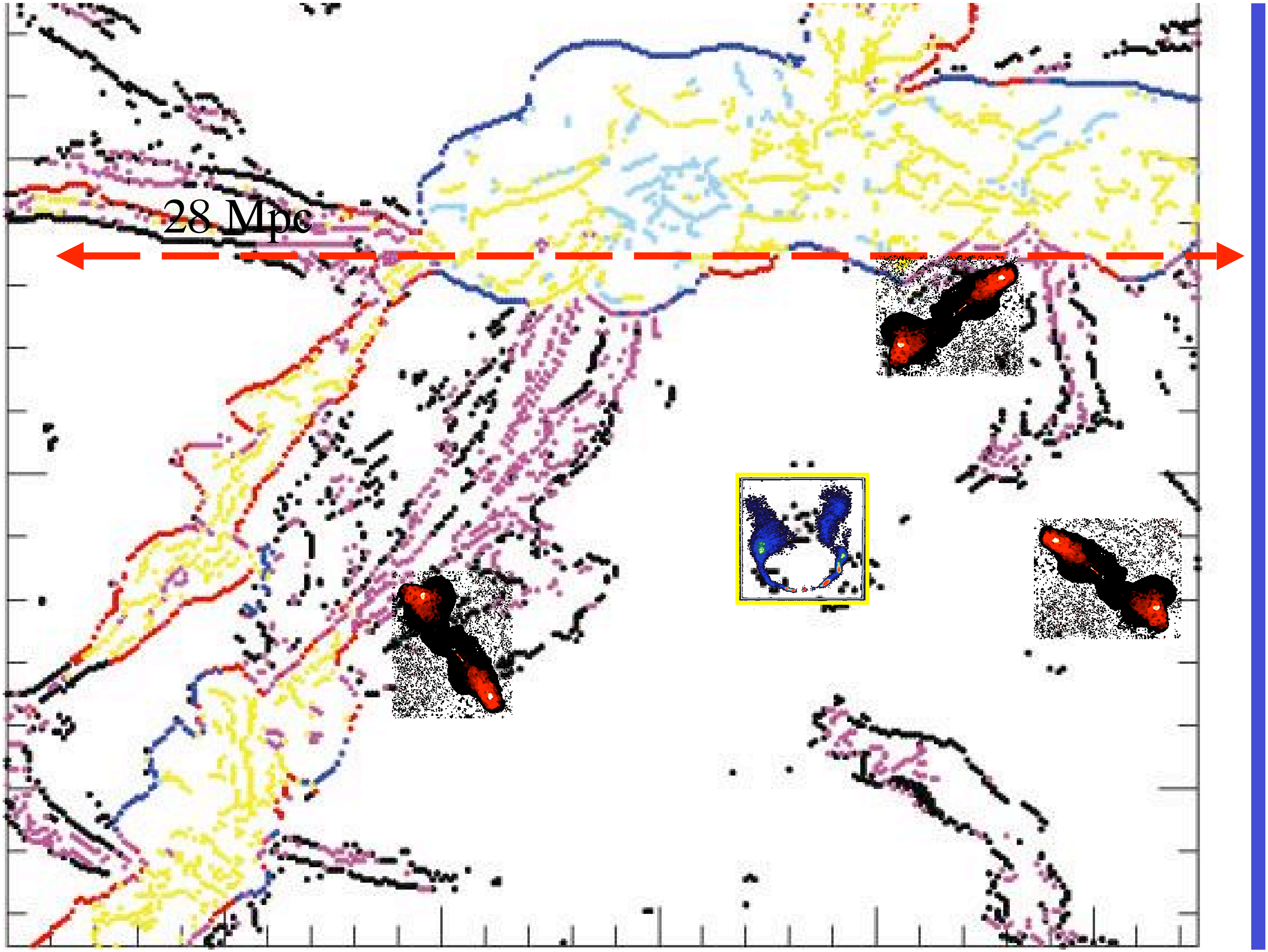
pressure



Li et al. 2005 (in preparation)



Ryu et al. 2005
28 Mpc


28 Mpc

Shocks vs AGNs

- **Thermal component:** 50% - all IGM (?)

Shocks: ~ 50-100 eV per baryon (from Ryu)

AGN: ~ 100 eV per baryon if

a) 0.01 efficiency SMBH energy release

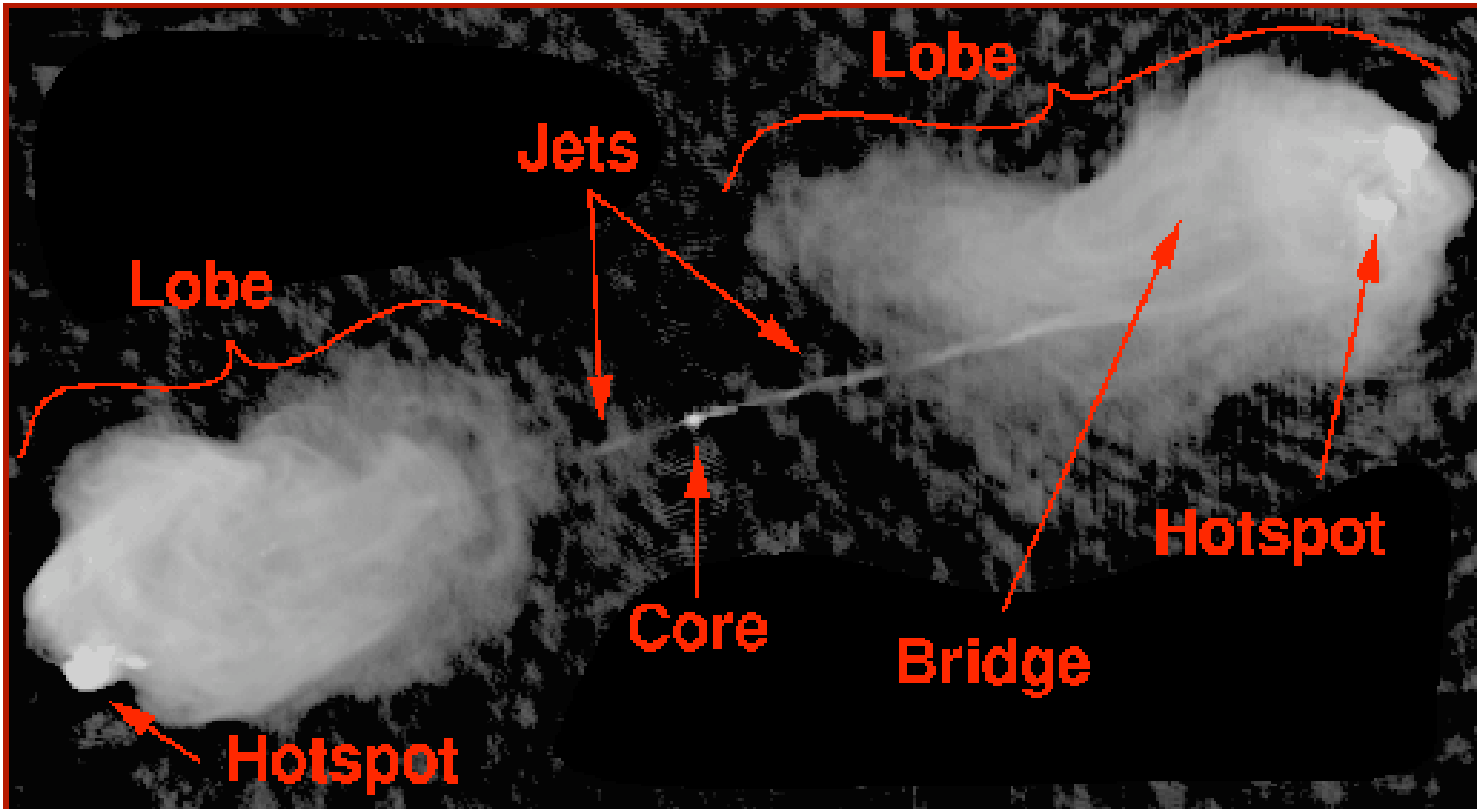
b) uniformly shared among all baryons ($\langle n \rangle \sim 10^{-6}$).

- **Nonthermal:** CR p/e, and magnetic fields.

Shocks: CR production (but need magnetic fields)

AGN (lobes): CR e, (p?) + magnetic fields

Topic I: Jets

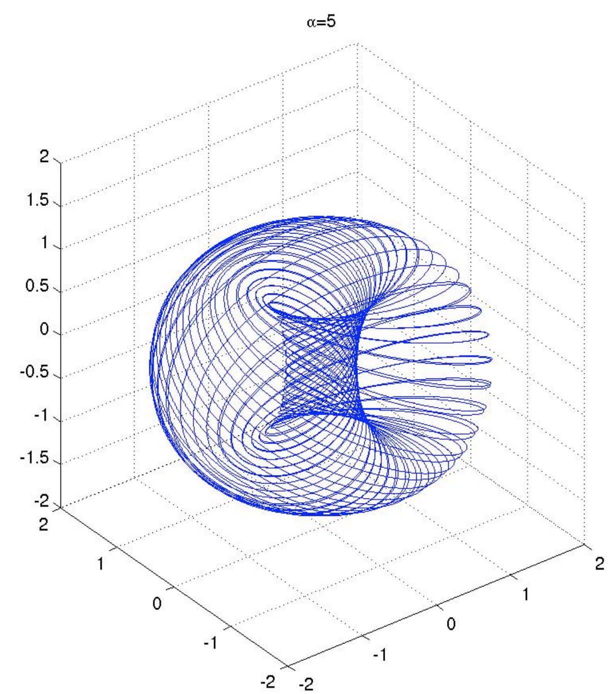


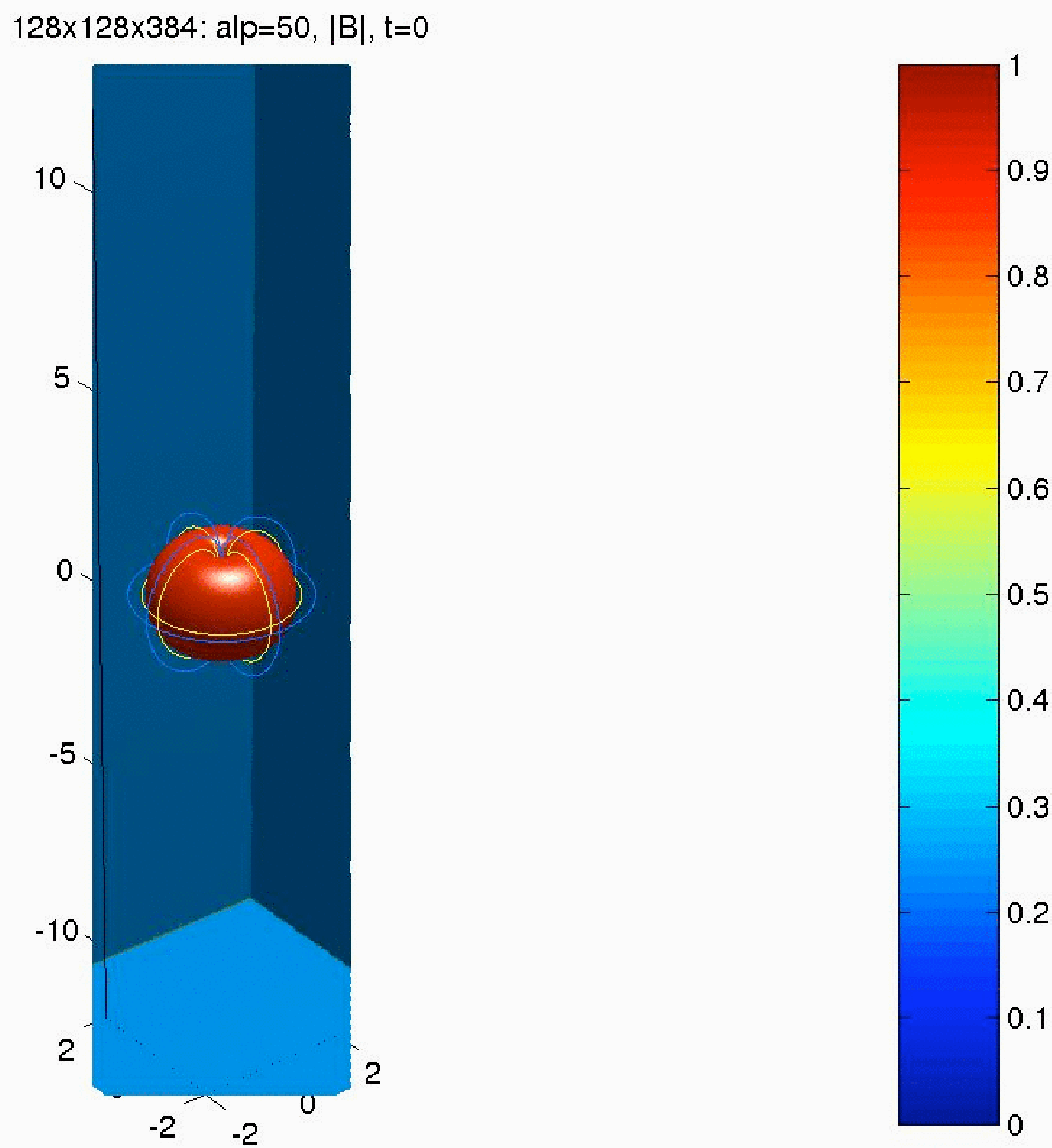
Physics of Astrophysical Jets

Focus: Global Configuration Evolution without modeling the accretion disk physics.

Approach: Replace accretion disk with a "magnetic engine" which pumps flux (mostly toroidal) and energy.

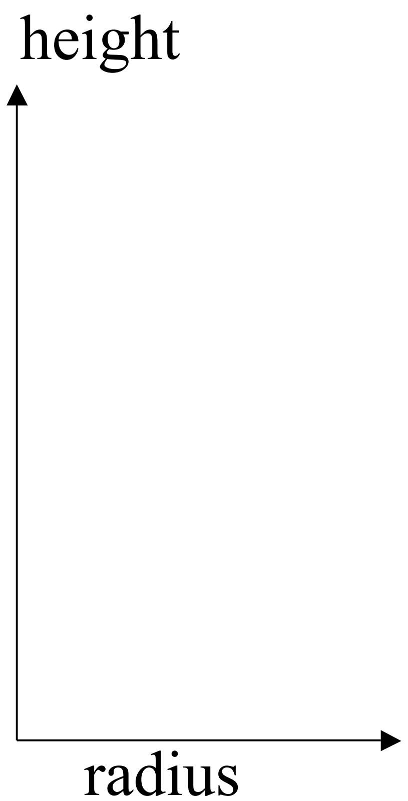
- **Impulsive Injection: Evolution of a highly wound and compressed magnetic "spring"**
- **Continuous Injection: Evolution of "magnetic tower" with continuous injected toroidal and/or poloidal fields**

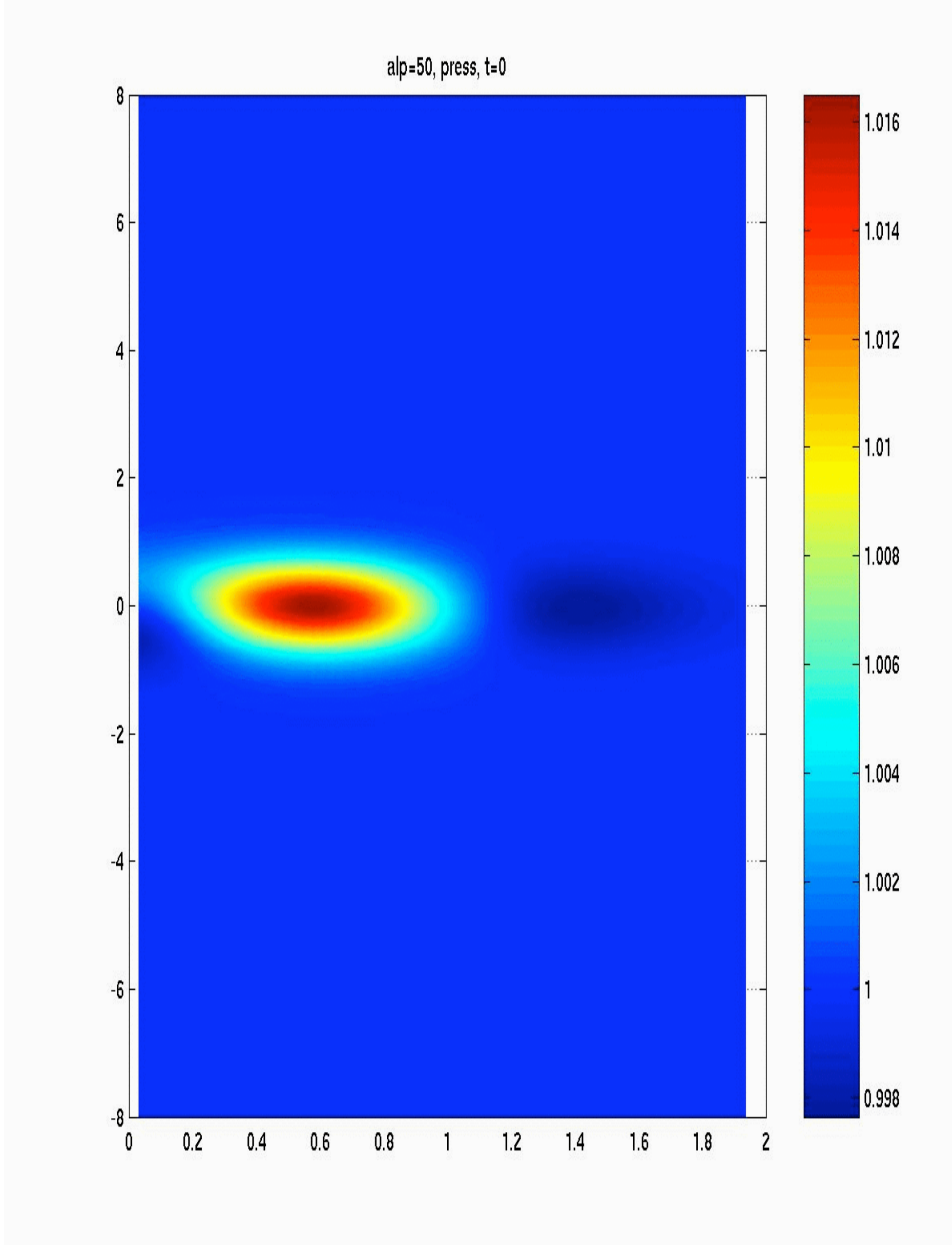


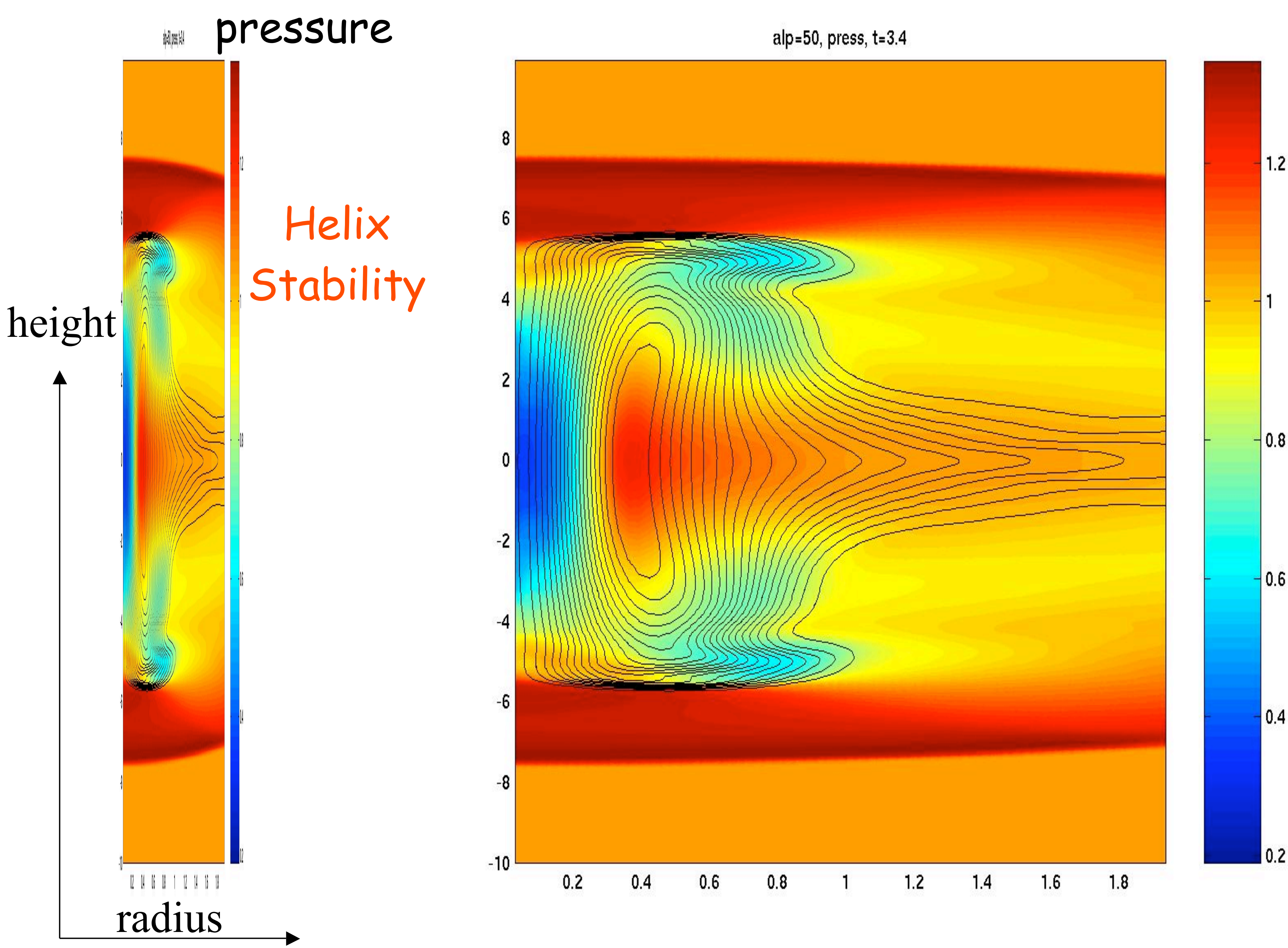


128x128x384: alp=50, |B|, t=0
10
5
0
-5
-10
2
-2
-2
0
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

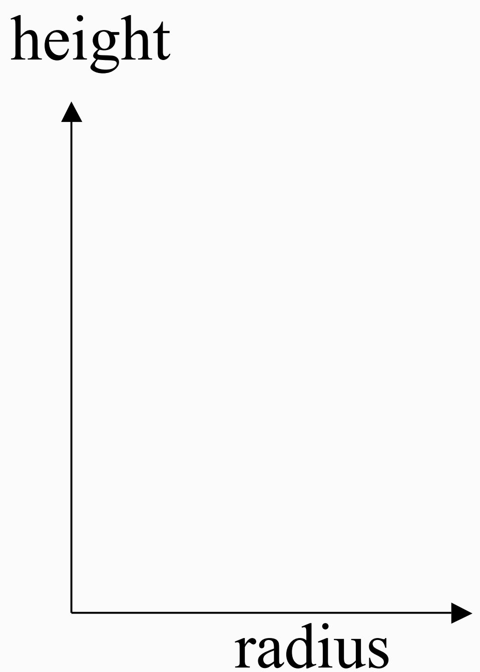
Pressure Evolution In Implusive Injection Case

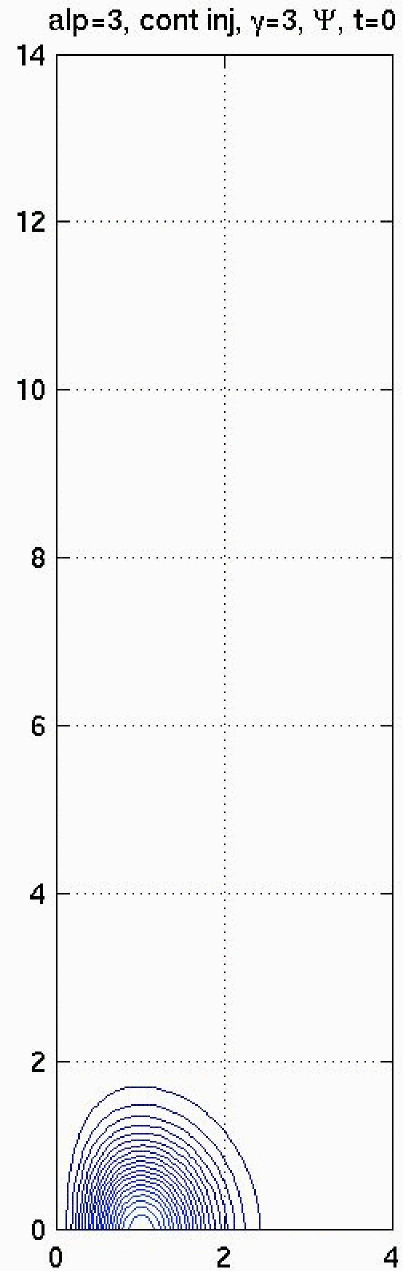




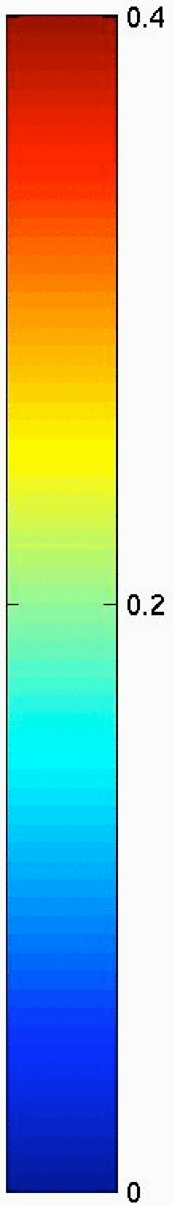

pressure
Helix
Stability
height
radius
alp=50, press, t=3.4
8
6
4
2
0
-2
-4
-6
-8
-10
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
1.2
1
0.8
0.6
0.4
0.2

Continuous Injection



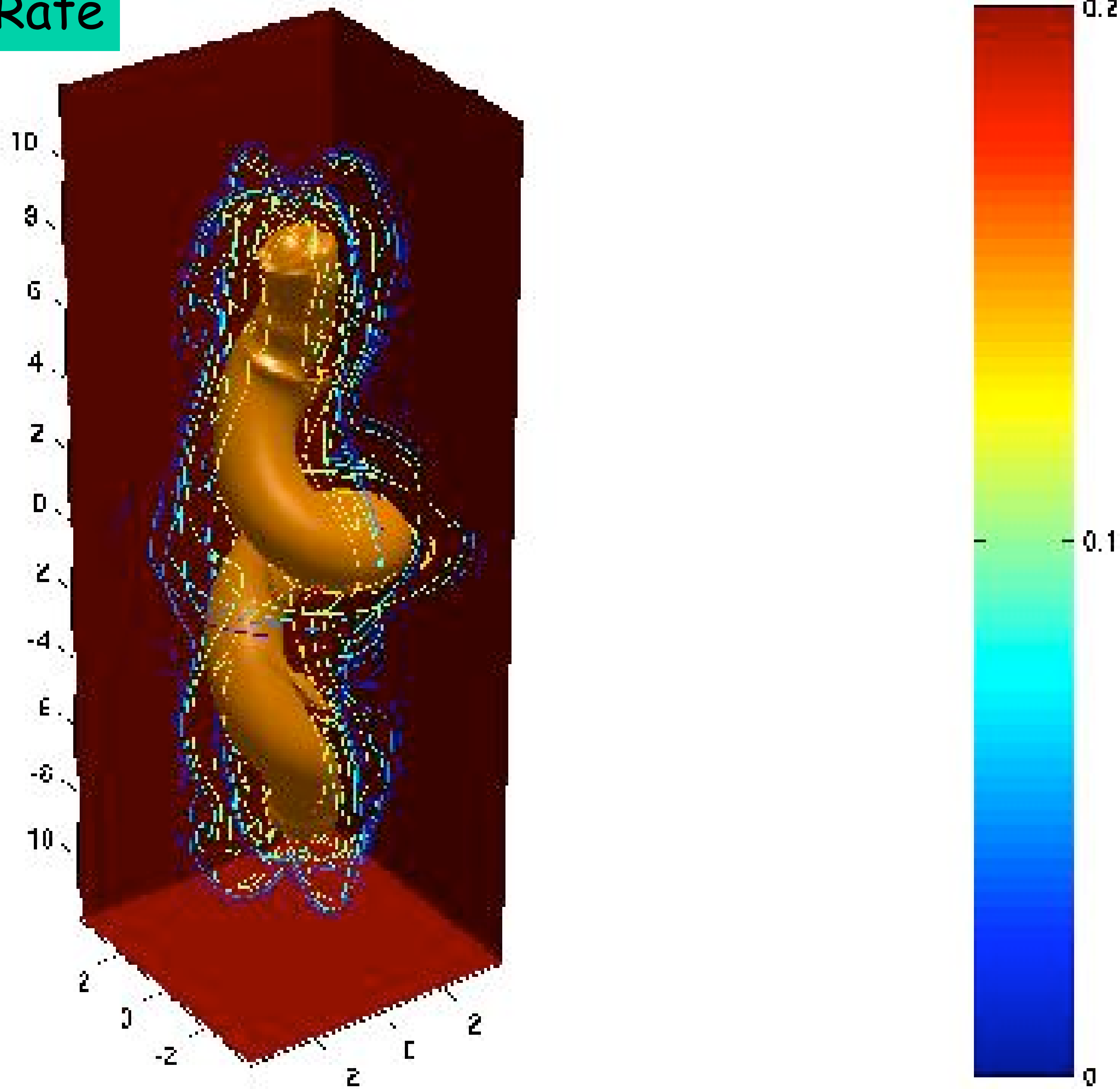


Azimuthally Averaged Poloidal Flux



High Injection Rate

Kink unstable



Simulations

- Inputs:

  a) ΛCDM+pure-Hydro: structure+galaxy formation, basis for SMBH population birth rate, location, and time.

  b) each SMBH modeled as injecting a magnetic bubble of E_B(M_{smbh},...) within a volume.

- Parameters:

  a) (10 Mpc)^3, 256^3, WMAP parameters, z=50-0

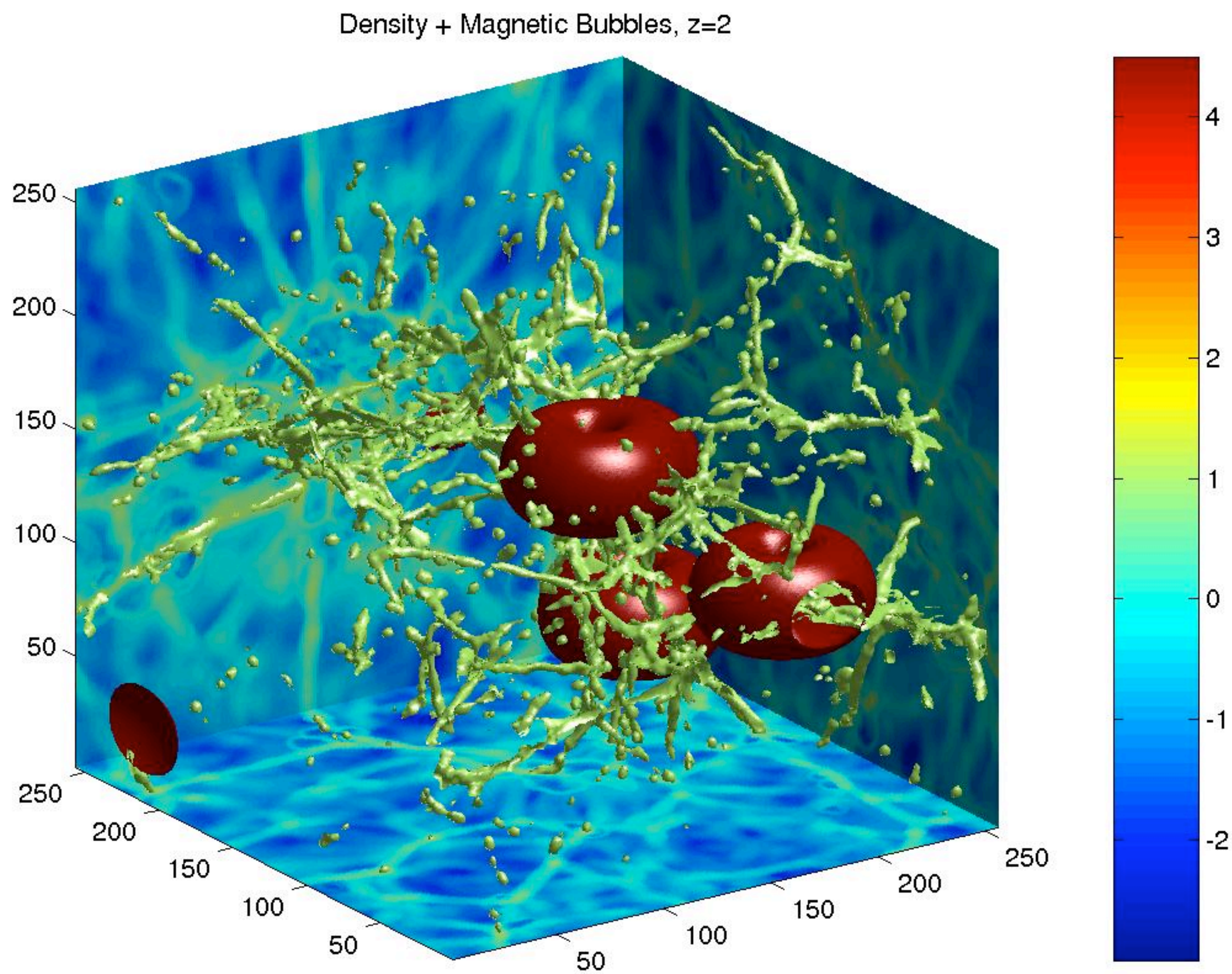
  b) injecting one bubble at z=2:

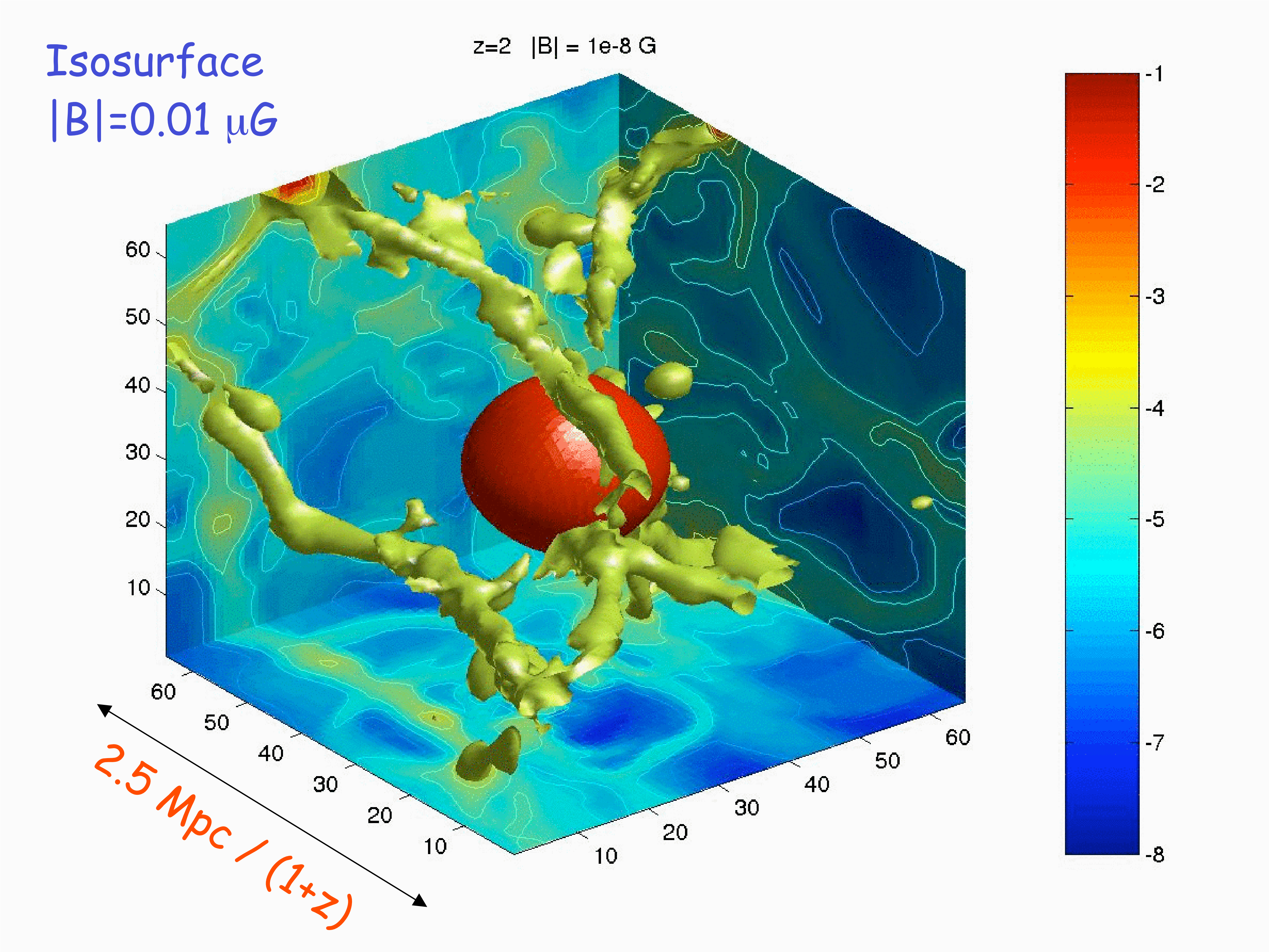
  $E_B \sim 10^{60}$ ergs within 50 kpc (proper frame)

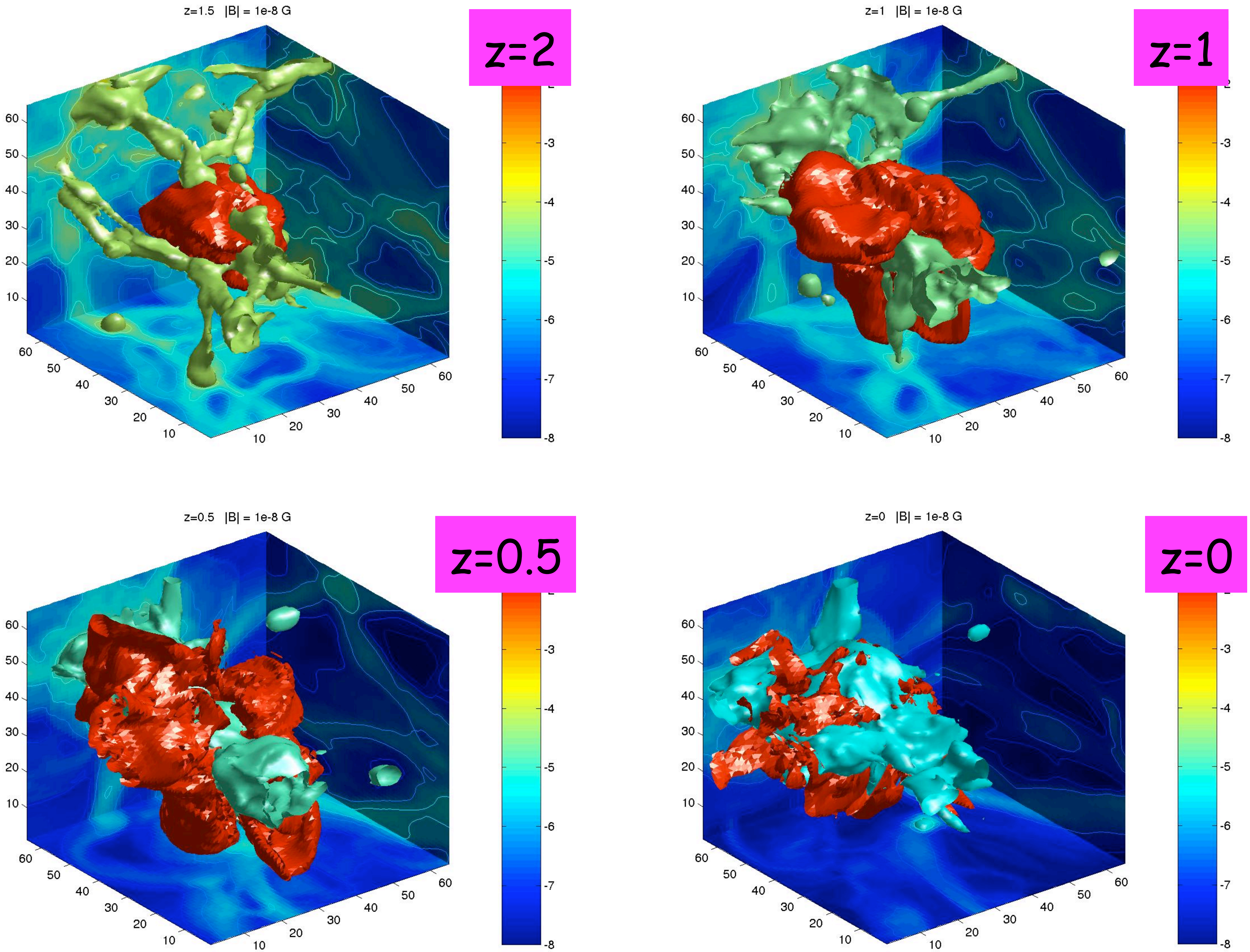
  c) initial $B_{max} \sim 10 \mu G$, $v_{Amax} \sim 3 \times 10^3$ km/s, $\beta_{min} = 10^{-2}$

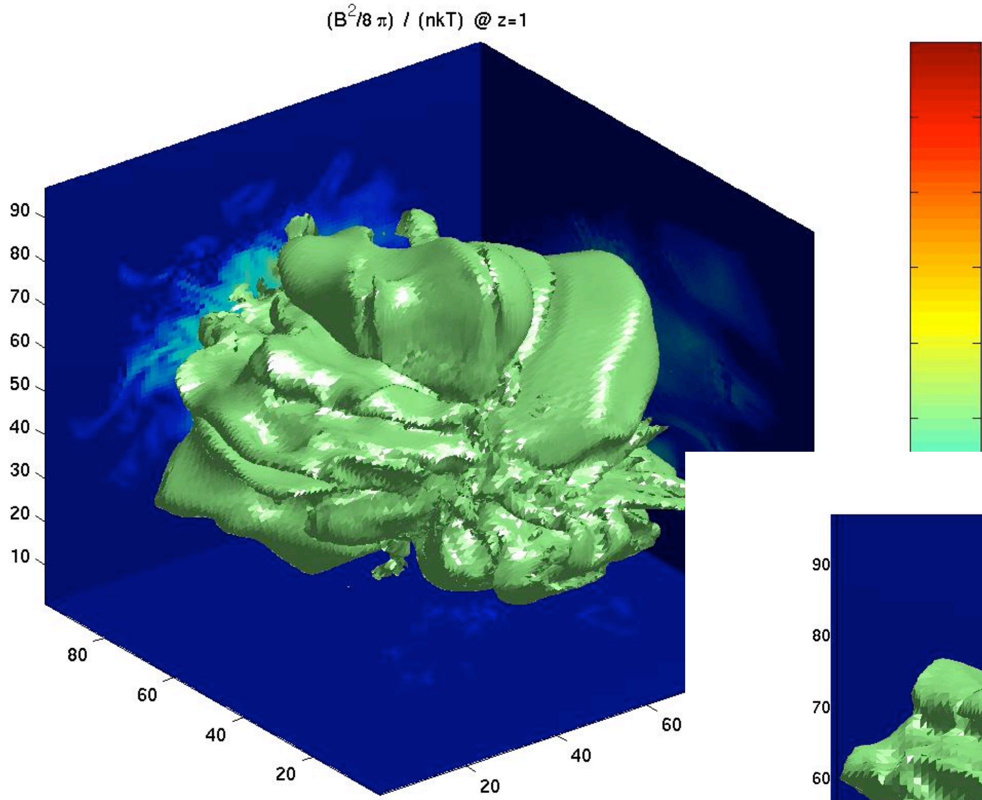
  d) $E_{th} \sim 10^{61}$ ergs within volume at z=2.

Grow "apples" on cosmic trees




Isosurface
|B|=0.01 μG
z=2 |B| = 1e-8 G
60
50
40
30
20
10
60
50
40
30
20
10
10
20
30
40
50
60
2.5 Mpc / (1+z)
-1
-2
-3
-4
-5
-6
-7
-8

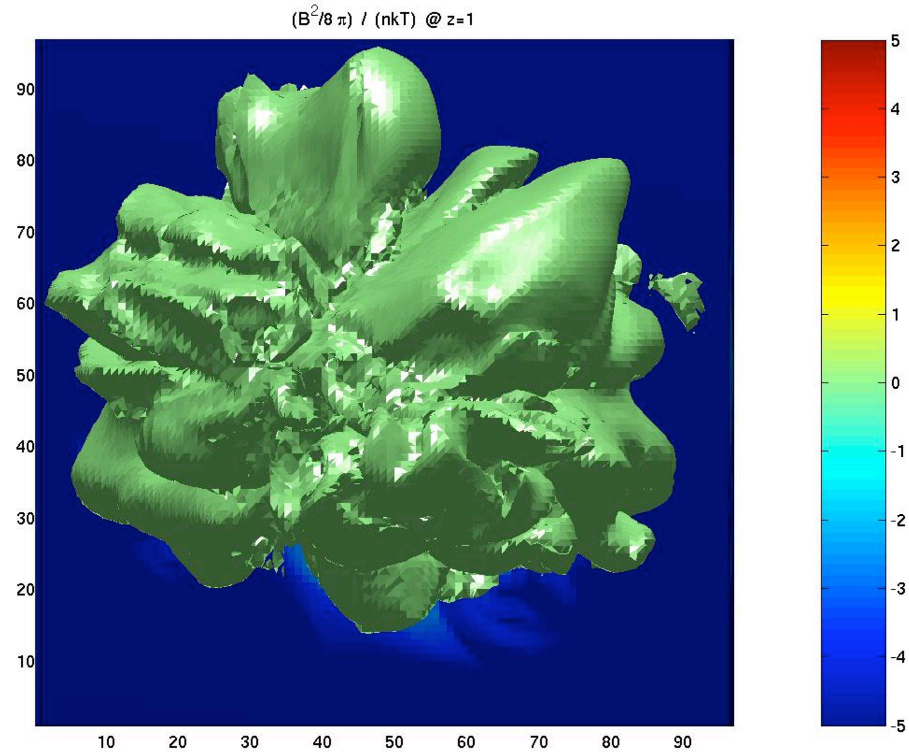

z=1.5 |B| = 1e-8 G
z=2
z=1 |B| = 1e-8 G
z=1
z=0.5 |B| = 1e-8 G
z=0.5
z=0 |B| = 1e-8 G
z=0



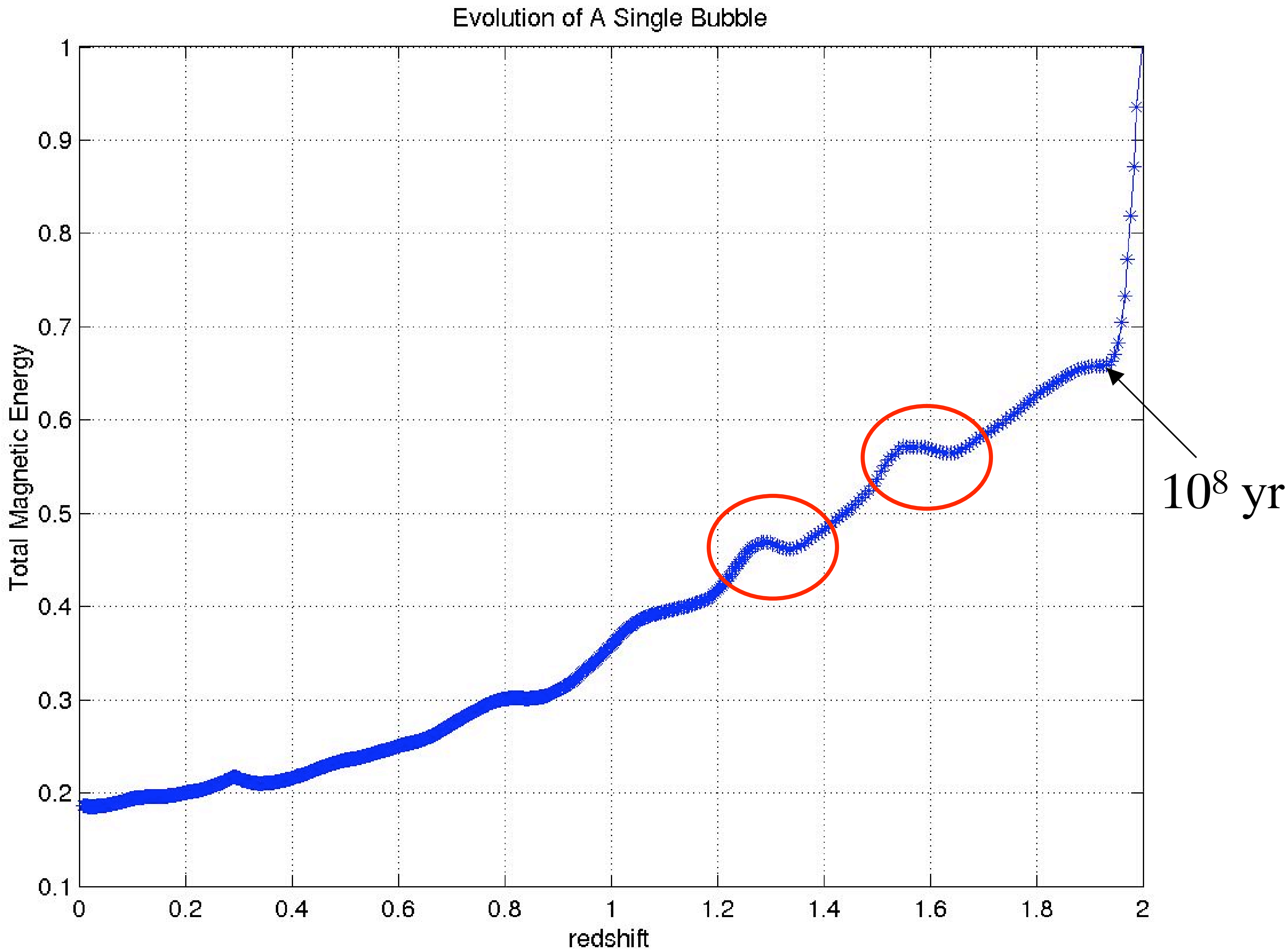
$$\frac{B^2}{8\pi} \Big/ nkT \quad @\ z{=}1$$

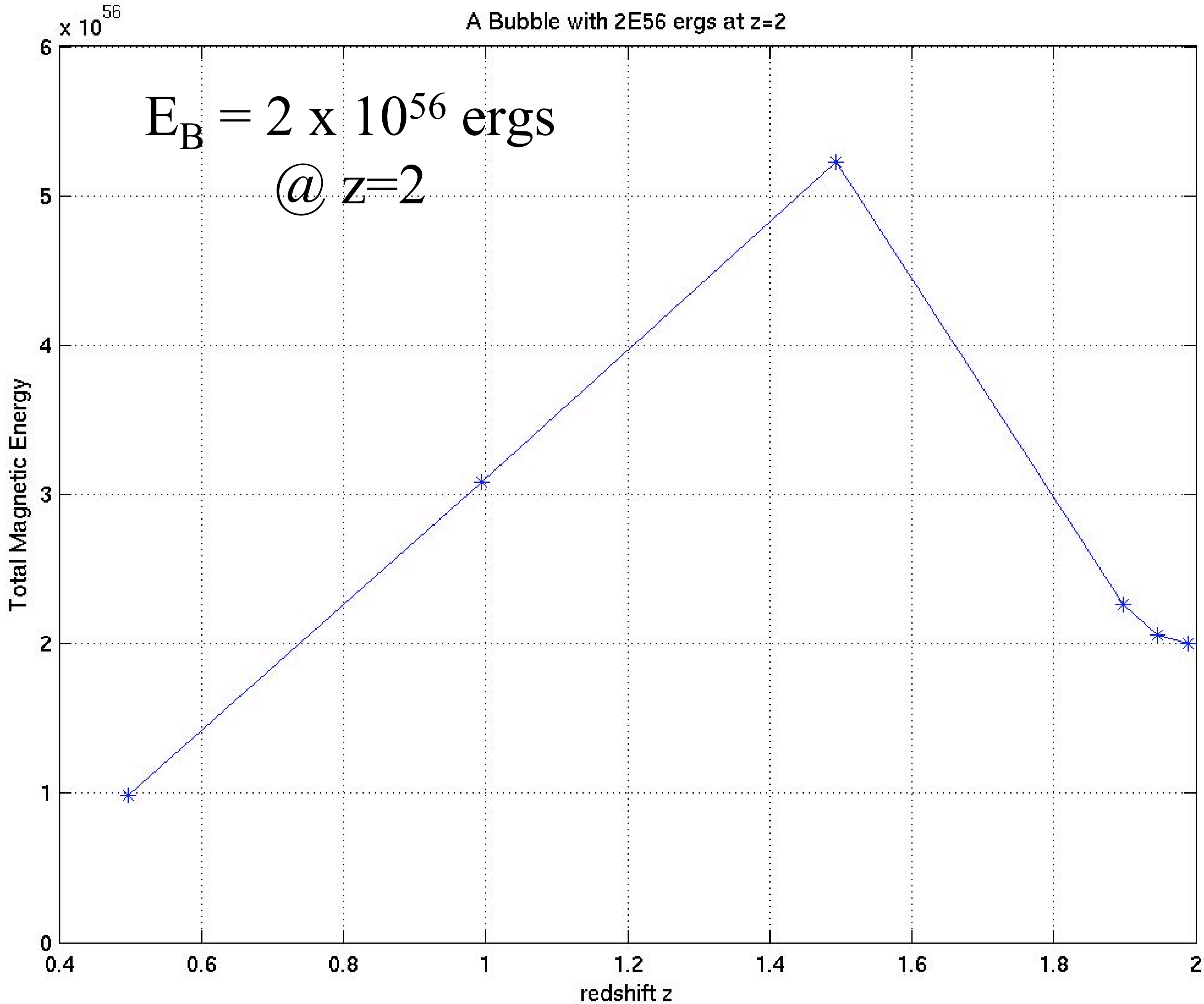
Injected 10^{60} ergs

@ z=2



3.8/(1+z) Mpc


Evolution of A Single Bubble
Total Magnetic Energy
redshift
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
10^8 yr


A Bubble with 2E56 ergs at z=2
x 10^56
E_B = 2 x 10^56 ergs
@ z=2
Total Magnetic Energy
redshift z
0
1
2
3
4
5
6
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Some Preliminary Implications

- In $(10\mathrm{Mpc})^3$ region, ~ 8 massive galaxies.
- From simulation, one bubble from one galaxy ~ $(1\ \mathrm{Mpc})^3$, so volume filling factor (at least) ~ $10^{-3} \times 8 \sim 1\%$.
- Dissipation timescale of magnetic fields
- Environment impact on lobes is quite strong
- Dynamo?

Summary

- Single lobe modeled as evolving from a magnetic spring.
- Self-consistent evolution in "realistic" IGM environment. IGM has a strong influence on the lobe shape/structure.
- Volume filling factor > 1% but more work needed.

Work in progress

- Detailed physical understanding of single lobe evolution
- Can this be studied in Laboratory experiments?
- Global simulations of the volume filling factor and heating of IGM by magnetic dissipation.
- Comparison with observations: syn., FRMs, relics, etc.
- Implications on CRs and losses by syn./IC losses.